

Large Geomagnetic Storms: Introduction to Special Section

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Abstract: Solar cycle 23 witnessed the accumulation of rich data sets that reveal various aspects of geomagnetic storms in unprecedented detail both at the Sun where the storm causing disturbances originate and in geospace where the effects of the storms are directly felt. During two recent coordinated data analysis workshops (CDAWs) the large geomagnetic storms ($Dst \leq -100$ nT) of solar cycle 23 were studied in order to understand their solar, interplanetary, and geospace connections. This special section grew out of these CDAWs with additional contributions relevant to these storms. Here I provide a brief summary of the results presented in the special section.

1. Introduction

The coordinated data analysis workshops (CDAWs) have been serving as a forum to analyze large and disparate data sets by members of the science community. Two such CDAWs were conducted in March 2005 (George Mason University) and 2007 (Florida State University) focusing on the set of all large geomagnetic storms ($Dst \leq -100$ nT) of solar cycle 23 until the end of 2005. There were 88 large storms in all [Zhang *et al.*, 2007]. The solar cycle 23 started in May 1996 and continued into 2008, although occasional observations active regions belonging to cycle 24 have been made since

December 14, 2007. After 2005, there have been only two additional large magnetic storms in cycle 23: one on April 14, 2006 with Dst \sim 111 nT and the other on December 15, 2006 with Dst \sim 146 nT. Thus the CDAW storms represent an almost complete set for the whole solar cycle. It was possible to assemble atmospheric, ionospheric, magnetospheric, interplanetary, and solar data on the 88 storms. The uniform and extended data on coronal mass ejections (CMEs) and the inner corona (including coronal holes) available from the Solar and Heliospheric Observatory (SOHO) mission has facilitated the study of solar connection of geomagnetic storms with unprecedented clarity. It must be noted that solar cycle 23 is the first cycle in which CME data are available over the whole cycle since the first detection of CMEs in the early 1970s. The availability of simultaneous space and ground based data covering the Sun-Earth space has made the solar cycle 23 storms as one of the best set of events that could serve as bench mark to compare storms of future and past cycles.

Papers constituting this special section fall into three groups addressing solar – interplanetary phenomena, magnetospheric phenomena, and ionospheric phenomena related to cycle 23 storms with a single exception dealing with an important storm from cycle 22 (Cliver et al., 2008). The superstorms of the Halloween 2003 and November 2004 periods are the subject of investigation in several papers.

2. Solar and Interplanetary phenomena

Asai et al. (2008) present a detailed examination of a peculiar active region (AR NOAA 10798) that emerged in the middle of a small coronal hole, and formed a sea anemone like configuration. Two successive CMEs from this active region caused a large geomagnetic storm (Dst = -216 nT) on 24 August 2005. The CMEs were very fast (1200

47 km/s for the first one and 2400 km/s for the second) as observed by SOHO. Based on the
48 height – time plots of the two CMEs, it was estimated that the CMEs interacted on the
49 way to Earth resulting in an interplanetary CME (ICME) with intense southward
50 magnetic field that was responsible for the large storm. It is suggested that the coronal
51 hole surrounding the active region might have channeled the CMEs with relatively
52 reduced friction between the solar wind and the CMEs.

53 Cliver et al. (2008) report on the solar source of the great geomagnetic storm ($Dst = -354$
54 nT) on 8-10 November 1991. The solar source is identified as the large-scale eruption of
55 a long ($\sim 25^\circ$) solar filament followed by a soft X-ray arcade that spanned $\sim 90^\circ$ of solar
56 longitude, distinguishing the geomagnetic storm as the largest yet associated with a
57 quiescent filament eruption. The storm was found to rank 15th on a list of Dst storms
58 from 1905 to 2004. The November 1991 event also underscores the difficulties in
59 predicting such storms.

60 Gopalswamy et al. (2008) report that many CMEs originating from close to the disk
61 center (within $\pm 15^\circ$ in longitude) do not arrive at Earth, while the shocks driven by them
62 do. Such “driverless” shock events occurred only during the declining phase of solar
63 cycle 23. In each case there was at least one large coronal hole near the eruption
64 suggesting that the coronal holes might have deflected the CMEs away from the Sun-
65 Earth line. The presence of abundant low-latitude coronal holes during the declining
66 phase further explains why these events were found in the declining phase. As a control
67 study, they also examined CMEs that originated close to the disk center and arrived at
68 Earth as shocks with drivers. For these, the coronal holes were located such that they
69 either had no influence on the CME trajectories, or they deflected the CMEs towards the

Sun-Earth line. Disk-center CMEs interacting with coronal holes were not geoeffective, while those minimally influenced by coronal holes were all geoeffective. This work demonstrates that in addition to source and kinematic properties of CMEs, one also has to consider the source environment in order to understand the geoeffectiveness of CMEs.

Jackson et al. (2008) present a low-resolution three-dimensional (3D) reconstruction of the 27-28 May 2003 halo CME sequence observed by Solar Mass Ejection Imager (SMEI) and the Solar and Heliospheric Observatory (SOHO) mission. These events are known to have caused a major geomagnetic storm on 2003 May 28 (see http://cdaw.gsfc.nasa.gov/CME_list/daily_plots/dsthtx/2003_05/dsthtx.20030528.html). From the reconstruction they were able to infer the shape, extent, and mass of this CME sequence as it reached the vicinity of Earth. The 3D reconstructed density, derived from the remote-sensed Thomson scattered brightness agrees well with the in situ measurements from the Advanced Composition Explorer (ACE) and Wind spacecraft. Bisi et al. (2008) apply the same reconstruction technique to the early November 2004 events and compare the reconstructed structures with in situ measurements from the ACE and Wind spacecraft, thus validating the reconstruction results. The early November 2004 events have caused two super intense ($Dst \sim -373$ nT and -289 nT) storms (Gopalswamy et al., 2006). Information derived from the reconstruction technique serve as input to the ENLIL 3D magnetohydrodynamic (MHD) numerical model of the solar wind.

92 Zhang et al. (2008) report on the multiple dips in the Dst index profile during the storm
93 interval. They studied the properties of the interplanetary drivers of 90 intense
94 geomagnetic storms during 1996 to 2006 to trace the cause of the dips. Since the
95 decrease in Dst index is caused by an interval of southward component of the
96 interplanetary magnetic field, multiple dips mean multiple intervals of southward
97 magnetic field within the overall storm interval. The majority of the 90 storms (66%)
98 showed two or more dips. One frequent cause of two-dip storms is the occurrence of the
99 southward field in the sheath and in the ICME such that the first dip is caused by the
100 sheath field while the second dip by the ICME. Double or multiple dips are also caused
101 by the presence of multiple sub-regions of southward magnetic field within a complex
102 solar wind flow, resulting from two successive, closely spaced ICMEs.

103 **3. Magnetospheric Phenomena**

104 Liemohn et al. (2008) report on the simulation of the intense magnetic storms from solar
105 cycle 23 using the hot electron and ion drift integrator (HEIDI) model. The simulations
106 were run using a Kp-driven shielded Volland-Stern electric field, static dipole magnetic
107 field, and nightside plasma data from instruments on the Los Alamos geosynchronous
108 satellites. The storms were analyzed by grouping them according to their solar wind
109 driver: ICMEs and corotating interaction regions (CIRs). They find that the HEIDI model
110 was able to best reproduce the Dst time series for storms driven by ICME sheaths. Storms
111 driven by CIRs were the least reproducible class of storms, with simulated minimum
112 Dst* values typically only half to two-thirds of the observed minimum value. In general,
113 there was a strong correlation between the observed and modeled minimums of Dst*, and
114 essentially no correlation between the observed minimum Dst* and the modeled-to-

115 observed Dst* ratio. One of the implications of this study is that a Kp-driven HEIDI
 116 simulation is consistently on the low side of predicting storm intensity, except for sheath-
 117 driven events.

118 Jordanova et al. (2008) study the effect of electromagnetic ion cyclotron (EMIC) wave
 119 scattering on radiation belt electrons during the large geomagnetic storm of 21 October
 120 2001 ($Dst = -187$ nT) using their global physics-based model. They calculate the
 121 excitation of EMIC waves (field-aligned and oblique) and evaluate particle interactions
 122 with these waves according to the quasi-linear theory. They find that pitch angle
 123 scattering by EMIC waves causes significant loss of radiation belt electrons at energies
 124 >1 MeV due to precipitation into the atmosphere. On the other hand, the relativistic
 125 electron flux dropout during the main phase of the storm at large L values (>5) is due
 126 mostly to outward radial diffusion. Global simulations indicate significant relativistic
 127 electron precipitation within regions of enhanced EMIC instability, whose location varies
 128 with time but is predominantly in the afternoon-dusk sector. The minimum resonant
 129 energy is found to increase at low L and relativistic electrons (<1 MeV) do not precipitate
 130 at $L < 3$ during the October 2001 storm.

131 Ilie et al. (2008) examine how the reference time selection affects the superposed epoch
 132 analysis (SEA) for intense storms at solar maximum. Analyzing solar wind data from
 133 ACE along with near-Earth data from the LANL MPA instruments, they find that for
 134 different choices of the time stamp, different storm characteristics are reproduced in the
 135 averaged data. In the ACE data they find that when using the storm sudden
 136 commencement (SSC) as a time reference, the SSC-related jump in solar wind
 137 parameters is very well reproduced, but near the storm peak, the vertical component of

the magnetic field (B_z) does not follow the criteria for intense storms ($B_z < -10$ nT for more than 3 hours). On the other hand, the B_z criterion is readily met when the zero epoch time is chosen near the storm peak, but the jump in solar wind pressure is not as sharp.

Keese et al. (2008) present time resolved, remote ion temperature measurements of the magnetosphere from $10 R_E$ to $-60 R_E$ for the 2000 October 4-7 storm. They calculate the ion temperatures from Maxwellian fits to IMAGE/MENA data. They find that the calculated ion temperatures in the magnetotail are consistent with in situ measurements from multiple geosynchronous spacecraft and GEOTAIL at $x = -9 R_E$. During the October 2000 storm, two separate instances of an Earthward propagating increase in ion temperature are found. When the solar wind-magnetospheric coupling is strong, the measured ion temperatures are consistent with predictions of a solar wind velocity correlation equation; at other times, the measured ion temperature is 2-3 times larger than the predicted value.

Manninen et al. (2008) investigate the steady magnetospheric convection period between the two episodes of the November 2004 superstorm. During the interval in question (18-04 UT on 8-9 November), the Dst index was stable but considerably low (-125 nT) and the B_z was steady and slightly negative (~ -5 nT). The strongest magnetic disturbances were observed in the midnight sector of the Earth, rather than in the expected morning side geomagnetic activity and Pc5 geomagnetic pulsations. The results were obtained using the Scandinavian multi-point observations of geomagnetic variations and pulsations, visible auroras, and energetic particle precipitation.

4. Ionospheric Phenomena

Ding et al. (2008) report on the large-scale traveling ionospheric disturbances associated with the major geomagnetic storms during 2002-2005. They use total electron content (TEC) perturbation maps obtained from more than 600 GPS receivers in North America (geographical latitudes of 25°N–55°N) and find 135 cases of such disturbances with amplitudes of up to 3.5 TECU and a maximum front width of ~4000 km. The mean velocity (300 m/s) is slower than that observed at lower latitudes. The occurrence of the disturbances peaks at 1200 LT and at 1900 LT. They also find that the UT dependence of the occurrence of auroral geomagnetic disturbances plays a major role in the forming of UT and LT dependence of the occurrence of the traveling ionospheric disturbances at midlatitudes. Perevalova et al. (2008) report on the large-scale traveling ionospheric disturbance registered in the auroral zone following the sudden storm commencement (SSC) related to the 29 October 2003 event. The disturbance represented a large-scale solitary type wave with an annular front shape whose center was located near the geomagnetic pole. They also detected a “swirling” effect in the disturbance movement in a direction opposite to the Earth's rotation.

Balan et al. (2008) report the occurrence of the F3 layer in the equatorial ionosphere at American, Indian, and Australian longitudes during the November 2004 superstorms (November 8 and 10). The observations show the occurrence, reoccurrence, and quick ascent to the topside ionosphere of unusually strong F3 layer accompanied by large reductions in peak electron density and total electron content. Observations and modeling indicate that the unusual F3 layers arise mainly from unusually strong fluctuations in the daytime vertical $E \times B$ drift.

183 Eriksson et al. (2008) report on an analysis of the great magnetic storm of 15 May 2005
 184 associated with a well-known magnetic cloud (Yurchyshyn et al., 2006) using DMSP,
 185 TIMED/GUVI, and IMAGE/WIC observations. In particular, they analyze the high-
 186 latitude response of sunward $E \times B$ flow and Birkeland field-aligned currents. Using
 187 DMSP observations, they were able to confirm a dawnward migration of a Northern
 188 Hemisphere sunward $E \times B$ flow channel between a downward and upward field aligned
 189 current pair. Using TIMED/GUVI observations, they also show that the dawnward
 190 migration of the upward field aligned current coincides with a drifting transpolar auroral
 191 arc.

192 Su. Basu et al. (2008) report on the impact of large ionospheric velocities on GPS-based
 193 navigation systems within the midlatitude region in the North American sector during the
 194 2004 November superstorm. The 2004 November storm was marked by the absence of
 195 appreciable storm-enhanced density gradients compared to the 2003 Halloween storms.
 196 This study demonstrates that it is possible to disable GPS-based navigation systems for
 197 many hours even in the absence of appreciable TEC gradients, provided an intense flow
 198 channel, generally known as the sub-auroral polarization stream (SAPS), is present in the
 199 ionosphere during nighttime hours.

200 Mannuci et al. (2008) report the prompt daytime ionospheric responses for four intense
 201 geomagnetic storms (during the 2003 Halloween period and 2004 November period).
 202 They perform a superposed epoch analysis of the storms and use measurements from the
 203 GPS receivers onboard the CHAMP satellite (400 km altitude) and from ground. The
 204 TEC data indicate significant low- to middle-latitude daytime TEC increases for three of
 205 the storms (~ 1400 local solar time) except for the 2003 November 20 storm, for which

206 the largest TEC increases appear several hours ($\sim 5\text{--}7$) following the Bz event onset.
 207 Estimates of vertical plasma uplift near the equator at Jicamarca longitudes ($\sim 281^\circ \text{E}$)
 208 suggest that variability of the timing of the TEC response is associated with variability in
 209 the prompt penetration of electric fields to low latitudes. They also found that for the
 210 November 2003 magnetic storm the cross-correlation function between the SYM-H index
 211 and the interplanetary electric field reached maximum correlation with a lag time of 4 h.
 212 Such long delays of both the ionosphere and magnetosphere responses need to be better
 213 understood.
 214 Pokhotelov et al. (2008) apply a novel technique of extracting the storm time $\mathbf{E} \times \mathbf{B}$
 215 convection boundary from in situ measurements of plasma bulk motion obtained by LEO
 216 DMSP satellites to the 20 November 2003 storm. They compare the results with the
 217 global distributions of the ionospheric plasma deduced from characteristics of GPS
 218 signals. The tomographic inversion of GPS data reveals that the convective flow
 219 expanded low enough in latitude to encompass, in part, the formation of the midlatitude
 220 TEC anomaly. Some features of the TEC dynamics observed during the 20 November
 221 2003 storm, however, suggest that mechanisms other than the expanded ionospheric
 222 convection (such as thermospheric neutral winds) are also involved in the formation of
 223 the midlatitude anomaly.
 224 Sahai et al. (2008a,b) report the effects of the November 2004 storms on the F-region in
 225 the Latin American and East Asian sectors. Virtually no spread F (phase fluctuations) on
 226 the nights of 09-10 and 10-11 November were observed in the Latin American sector.
 227 The East Asian sector showed very pronounced effects during the second superstorm
 228 which was preceded by two intense storms. There was no spread-F in the Vietnamese

sector, but a strong spread-F in the Japanese sector suggesting the behavior of the nighttime F-region during intense geomagnetic disturbance could be very different in close-by longitudinal sectors.

Zhao et al. (2008) investigate the ionospheric disturbances in the Southeast Asian region during the super magnetic storm of 20–22 November 2003 using an ionosonde chain and a GPS network assisted by space-borne instruments. They report that the equatorial ionosphere was elevated to a very high level during the storm. The penetration efficiency of the interplanetary electric field to the equatorial ionosphere was larger at night than in the daytime. During the recovery phase, the interplanetary electric field was severely inhibited owing to a wind convergence and possibly because of the westward disturbance dynamo electric field.

Villante and Regi (2008) report on the remarkable solar flare effect (SFE) due to the 28 October 2003 solar flare that caused increased photoionization effects in the dayside ionosphere. The aspects of the SFE onset and initial phase reveal a close correspondence with those of the EUV flux. At equatorial/electrojet latitudes, the SFE manifestation can be mostly interpreted in terms of a significant enhancement of the pre-flare current system during normal electrojet conditions, with some evidence for a highly confined counter electrojet in the dawn sector. Additional elements, at higher latitudes, might suggest in these regions a more significant role of the X-ray flux and the onset of additional currents below the normal dynamo current region.

5. Conclusion

Results presented in this special section represent the complexity arising from interactions between the solar, interplanetary, magnetospheric and

ionospheric/thermospheric regions during large storms. The dynamic range provided by these storms continues to yield better insight into their physics and stand testimony to the multi-disciplinary effort required to gain a complete understanding of the storms. Such efforts are expected to continue with the complete data base accumulated on the large geomagnetic storms available to the scientific community for further analysis.

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